ELECTROMAGNETIC WAVES

PREFACE

All the physical quantities we have discussed so far were "built" out of four "dimensions"

Length (L), Time (T), Mass (M) and Temperature (θ)

To proceed further we need to introduce a new fundamental "DIMENSION" called

CHARGE → Q

by asserting that in addition to Mass (M), matter has another intrinsic property called:

→ Charge Q Coulomb (C) scalar

Details will be worked out later but for now we need to know that a charge creates two kinds of fields just as a mass creates a Gravitational field (which gives Newton's law).

A stationary charge creates a Coulomb $\vec{E}$ field

→ E $MLT^{-2}Q^{-1}$ Newton/Coulomb VECTOR.

A moving charge creates a $\vec{B}$ field

→ B $MQ^{-1}T^{-1}$ TESLA VECTOR.

As we shall learn later, when an $\underset{\sim}{E}$ field changes in space and time it creates a $\underset{\sim}{B}$ field and when a $\underset{\sim}{B}$ field changes in space and time it creates a Non-Coulomb $\underset{\sim}{E}$ field and the two of them cannot stay put, they must travel in the form of waves called

"Electromagnetic Waves"

Electromagnetic waves are everywhere: Radio waves, Television, microwaves, heat radiation, light, UV, x-rays, γ-rays. (see below).

ELECTROMAGNETIC (EM) WAVES
→ LIGHT

INTRODUCTION: So far we have discussed mechanical waves, that is, waves which require matter for the propagation of the disturbance, or deviation from equilibrium. EM waves are totally different in that they travel in VACUUM. Indeed, by and large, we will only discuss properties of EM waves in vacuum. The complexities of EM waves travelling through a medium are too advanced for our discussion.

So as noted in the preface, what travels in an EM wave. In more conventional presentation one first discusses details of $\underset{\rightarrow}{E}$ - fields (electric fields) and $\underset{\rightarrow}{B}$ - fields (magnetic fields) before one gets to EM-waves but the present text introduces EM waves very early so for the present all we can say is that a travelling EM-wave involves propagating $\underset{\rightarrow}{E}$ and $\underset{\rightarrow}{B}$ fields and defer the proper understanding of the fields till later. The $\underset{\rightarrow}{E}$ and $\underset{\rightarrow}{B}$ fields represent the disturbances in the vacuum and are functions of x and t such that x and t appear in the combination

$$(x \mp vt)$$

So that such fields must propagate with velocities $\pm v\hat{x}$ by definition of a travelling wave.

Periodic EM waves

As before a periodic EM wave will be represented by

$$\underline{E} = \underline{E_m} \sin\left(\frac{2\pi x}{\lambda} \pm \frac{2\pi t}{T}\right) = \underline{E_m} \sin(kx - \omega t) \quad -(1)$$

and

$$\underline{B} = \underline{B_m} \sin\left(\frac{2\pi x}{\lambda} \pm \frac{2\pi t}{T}\right) = \underline{B_m} \sin(kx - \omega t)$$

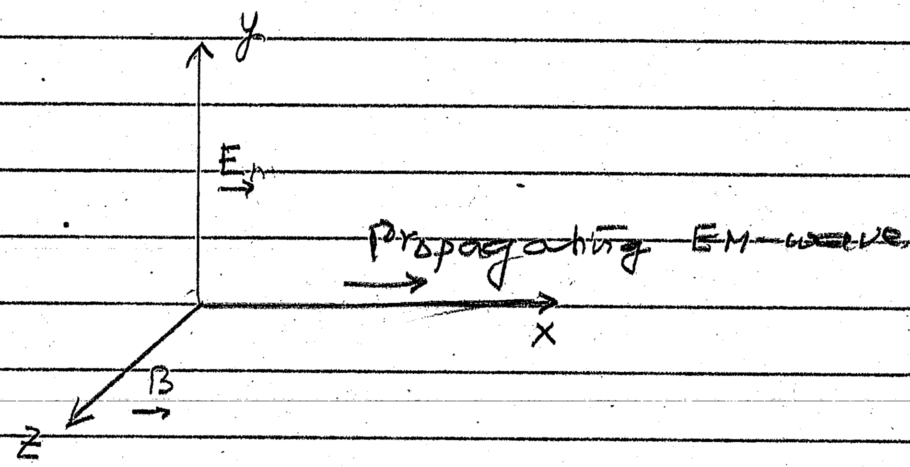
with $k = \frac{2\pi}{\lambda}$, $\omega = \frac{2\pi}{T} = 2\pi f$ — (2)

and the speed $v = \lambda f$ or $\omega = vk$. —(3)

In vacuum EM-waves are totally transverse:

$$\underline{E_m} \perp \hat{x}$$
$$\underline{B_m} \perp \hat{x}$$
$$\underline{E_m} \perp \underline{B_m}$$

Indeed for a wave travelling in +ive x direction $\underline{E_m} \parallel \hat{y}$ and $\underline{B_m} \parallel \hat{z}$



In vacuum EM-waves have an enormous speed (symbol c)

$$C = 3 \times 10^{8} m/sec. \qquad (4)$$

In vacuum the $\underline{E}$ and $\underline{B}$ fields are related by the equation

$$E = cB \qquad (5)$$

The EM wave also transports energy because energy is stored in the $\underline{E}$ and $\underline{B}$ fields.

Later we will prove that per m^3 the fields carry the energies

$$\eta_E = \frac{1}{2} \epsilon_0 E^2 \qquad (6)$$

$$\eta_B = \frac{B^2}{2\mu_0} \qquad (7)$$

Here, ϵ_0 and μ_0 are constants, roughly,

$$\epsilon_0 = 9 \times 10^{-12} \; F/m \qquad (8)$$

ϵ_0 $\quad Q^2 M^{-1} L^{-3} T^{+2}$ $\quad F/m$ $\quad$ scalar

$$\mu_0 = 4\pi \times 10^{-7}\ H/m \qquad (9)$$

(μ_0 MLQ^{-2} H/m scalar)

It is notable that speed of EM wave

$$c = \frac{1}{\sqrt{\mu_0 \epsilon_0}}$$

so that, because of Eq (5), in an em wave

$$\eta_E = \eta_B \qquad (10)$$

Hence $1m^3$ of an EM-wave carries the energy

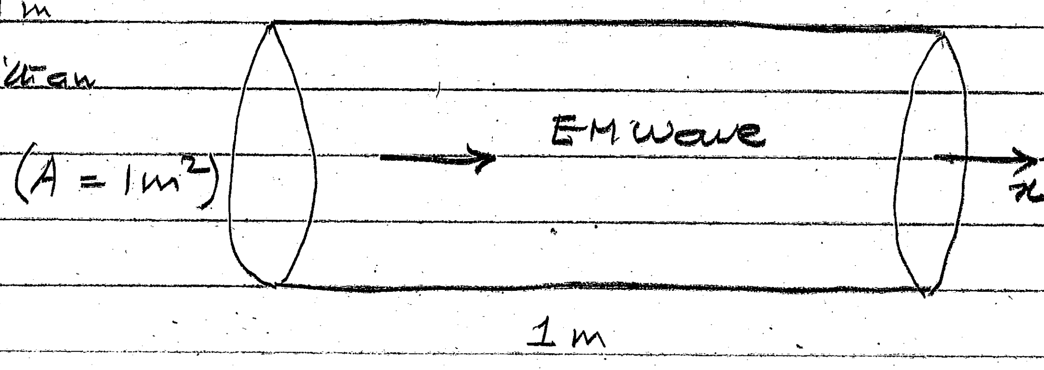
$$\eta_{EM} = \eta_E + \eta_B = \epsilon_0 E^2 = \frac{B^2}{\mu_0} \qquad (11)$$

As in the case of sound we can calculate the Intensity of an EM-wave by using (11):

Intensity = Energy transport per unit area per unit time.

So imagine a tube of cross-sectional area $1m^2$

"filled" with an em wave



If its length is 1 m then at any instant the energy stored in it is

$$\eta_{EM} = \epsilon_0 E^2 = \frac{B^2}{\mu_0} \qquad (12)$$

where $E^2 = E_m^2 \sin^2(kx - \omega t)$

$B^2 = B_m^2 \sin^2(kx - \omega t)$.

The average value of the energy will be

$$\langle \eta_{EM} \rangle = \epsilon_0 E_m^2 \langle \sin^2(kx - \omega t) \rangle \qquad (13)$$

$$= \frac{B_m^2}{\mu_0} \langle \sin^2(kx - \omega t) \rangle$$

But $\langle \sin^2(\;) \rangle = \frac{1}{2}$

so

$$\langle \eta_{EM} \rangle = \frac{\epsilon_0 E_m^2}{2} = \frac{B_m^2}{2\mu_0} \qquad (14)$$

In one second this energy will travel by c meters so energy transport per m^2 per second becomes

$$\langle I \rangle = \frac{c \epsilon_0 E_m^2}{2} = \frac{c B_m^2}{2\mu_0} \qquad (15)$$

<u>Spectrum of EM-waves – LIGHT</u>

EM waves are essentially ubiquitous – radio waves, UHF waves, microwaves, heat radiation (infra-red waves), light, ultra violet, X-rays, γ-rays – are all EM waves.

The following table illustrates this point succinctly.

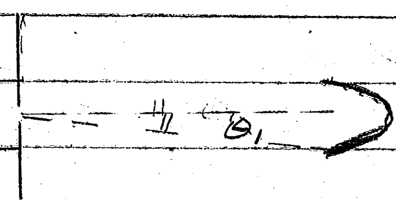
Name	Frequency	Wavelength (in vacuum)
AM radio	100 kHz	kms
FM radio	100 MHz	3 m
TV – UHF	300 MHz	1 m.
MICROWAVES	1 – 100 GHz	0.1 m — 0.003 m.
INFRARED (HEAT RADIATION)	$10^{12}-10^{13}$ Hz	10^{-5} m.
→ LIGHT	$10^{14}-10^{15}$ Hz	400 nm — 700 nm.
UV	$10^{16}-10^{17}$ Hz	100 nm.
X-rays	10^{18} Hz	1 nm
γ-rays	10^{20} Hz	1 pm

To Summarize:

What is light? : Light is a transverse em wave whose wavelength in vacuum (air) lies between 400 nm and 700 nm and speed in vacuum is 3×10^8 m/s.

Geometrical optics

Like any other wave, when light of wavelength λ
goes through an opening of width w, it will spread out over an angle θ_1 given
by $\sin\theta_1 = \left(\frac{\lambda}{w}\right)$



so if $w \gg \lambda$, $\theta_1 \to 0$

and there will be no measurable spreading. In that case, light will appear to be travelling along a straight line (in accord with Fermat's principle of least time) hence talk of light RAY. This is the basis of the science of geometrical optics — all the openings and obstacles encountered by the wave must be much larger than the wavelength of light.

We will first discuss wave optics and then geometrical optics and give you a proper theoretical basis for the two experiments you have done.